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This report reviews our effort to develop an advanced multiscale and multifidelity Modeling & Simulation (M&S) capability targeted at the fundamental studies of the physical characteristics of Field Reversed Configuration (FRC) plasma for advanced space propulsion. This effort consists of numerical model development, physical model development, and systematic studies of the non-linear plasma dynamics and finite rate processes governing FRC formation, acceleration, stability and interaction with the environment.

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**Annual Report 2014**
**High Fidelity Modeling of Field-Reversed Configuration (FRC) Thrusters**
Report Start Date: 10/01/2013

Report End Date: 09/30/2014

Justin Koo, AFRL/RQRS

This report reviews our effort to develop an advanced multiscale and multifidelity Modeling & Simulation (M&S) capability targeted at the fundamental studies of the physical characteristics of Field Reversed Configuration (FRC) plasma for advanced space propulsion. This effort consists of numerical model development, physical model development, and systematic studies of the non-linear plasma dynamics and finite rate processes governing FRC formation, acceleration, stability and interaction with the environment.

The Field-Reversed Configuration (FRC), a type of closed-field plasmoid (CFP) is a self-organized magnetized plasma configuration in the shape of a highly compact toroid, characterized by the presence of closed magnetic field lines and a high ratio of toroidal to poloidal current. To date, a limited number of laboratory thrusters have demonstrated the feasibility of using FRCs for propulsion application. Two of the most advanced designs are based on the theta-pinch formation and the RMF formation mechanism, which forms the plasmoid through the induced electron current from a rotating magnetic field (RMF) as shown in Figure 1.
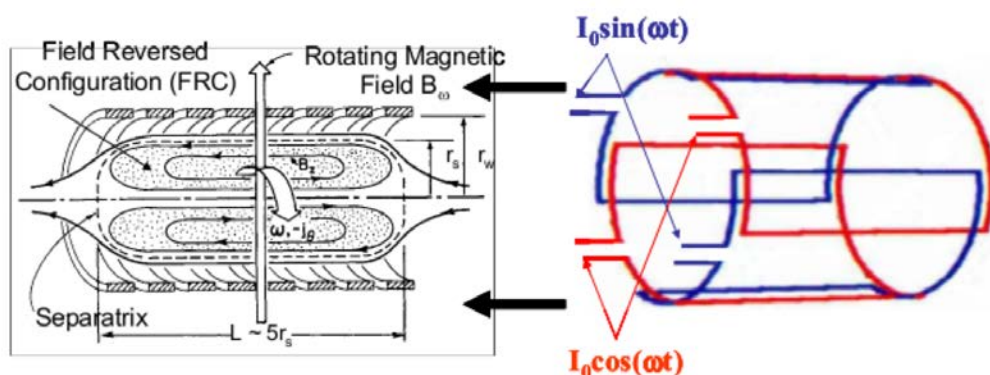


*Figure 1. Schematic of RMF FRC thruster (left) and typical saddle coil geometry (right)*

While the use of FRCs as a high efficiency/high thrust successor to the current generation of Electric Propulsion (EP) devices (HETs and Ion thrusters) holds great promise, especially as the foundation of a true hybrid chemical/electric propulsion capability, the need to optimize these devices for relatively low (1-10kW power levels) to make them relevant to modern satellites requires a much more comprehensive understanding of the fundamental physics of these devices. To achieve this understanding, it is necessary not only to construct a consistent hierarchy of plasma models describing the complex behavior of magnetized partially ionized plasmas, but also to develop an extensive suite of ancillary physics models (coil models for accurate evaluation of mutual inductance and Collisional-Radiative (CR) models for spectroscopic validation) to effectively study real FRC devices.

There are major phases of FRC thruster operation – pre-ionization, formation and translation. Each phase of FRC operation is associated with a set of technical challenges which in turn translate into several areas of focus of our research program. These include the field/plasma model, collisional physics, multiscale effects and the overall system complexity. During this period, we have focused largely on the formation phase of the FRC, both from a fully kinetic and also from a fluid perspective.

From the fully kinetic perspective, development has focused on the use of the numerical simulation of neutral entrainment in an FRC thruster with a neon propellant. A fully kinetic approach based on a Particle-In-Cell method of modeling plasmas and the Direct Simulation Monte Carlo method of modeling neutrals was applied. To perform the fully kinetic simulations, an implicit PIC code, Celeste3D, was extended to compute neutral transport and collision processes between neutral and charged particles. The collision models included all key elastic, collisional radiative, and reaction processes in neon.

The resulting two-dimensional modeling of the FRC neutral entrainment showed strong entrainment for neutral densities exceeding 5E18 $m^3$; with momentum transfer and thruster efficiency being non-linear functions of neutral density. The probability of neutral atom collision with the plasmoid was estimated at approximately 10%, with most of the collisions being charge exchange events. Electron impact ionization is not significant for a 5 eV plasmoid, but becomes a factor at 10 eV. For neutral gas injected in a 10% area of the chamber, the ion contribution to thrust was found to decrease by up to 30% due to the plasma-neutral momentum transfer when neutral density was increased to 2.5E19 $m^3$.

We have begun our fluid development by focusing on the development of a high order Multifluid (MF) method (based on the WarpX framework from the University of Washington) in order to more efficiently address the full timescale for FRC formation. This work has been greatly expedited through the hiring of two new employees, Dr. Eder Sousa (recent graduate of U. of Washington) and Dr. Artan Qerushi (formerly at Tri-Alpha). The initial work of these two hires has been focused on theoretical development efforts with further details presented in the Attachments section.

**Attachments (These documents were presented outside of the reporting timeframe but represent work accomplished during the reporting period.)**

- Brackbill, J., et al, "Numerical Analysis of Neutral Entrainment Effect on Field-Reversed Configuration Thruster Efficiency, Journal of Propulsion and Power, Vol 30, No. 6, Nov-Dec 2014.
- Qerushi, A, "Overview of FRC-Related Modeling (July 2014-Present)", RQ-West 6.1 Research Review (20 Jan 2015, Los Angeles, CA)
- Sousa, E, "The Discontinuous Galerkin Finite Element Method for Multi-fluid Plasma Modeling", RQ-West 6.1 Research Review (20 Jan 2015, Los Angeles, CA)